FEC for low-rate satellite links

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Phil Karn, KA9Q
karn@ka9q.net
http://www.ka9q.net

Not new!

- I've been championing this for years
- Designed AO-40 FEC format 2002
  - 1/4-wave S-band ground plane at apogee
- No known amateur satellites since
  - always a little too late for each new satellite...
- Should be absolutely standard
  - standard for decades outside ham radio
  - No more AFSK/FM!!!

Why FEC?

- Reduced spacecraft energy per bit:
  - smaller DC power requirements and/or
  - smaller receive antennas and/or
  - Improved link margin and/or
  - Higher data rates
- *Well* within PC capability
  - I did 434 bps ACE RTSW decoder (k=7) in 1999, runs on low-end Pentium
  - STEREO (k=15 Viterbi) in real time

S/C Power Is Expensive!!

- Solar panels: ~$1000/watt
- Geometric loss:
  - 1 (steerable flat panel normal to sun)
  - 1/6 (cube with one face normal to sun)
- BCR: ~90%; NiMH battery: ~85%, ~70 Wh/kg
- HPAs: 10-50%, depending on linearity
- LEO launch costs ~$10,000/kg
  - gold US $23,000/kg

Terminology

- Forward Error Correction (FEC):
  - Structured redundancy for receiver correction of errors without retransmission
- **Bit**: user data bit
- **Symbol**: data bit from encoder output
  - modems handle symbols, not bits
- **Code Rate**: bit rate / symbol rate
  - e.g., rate ½ = 2 channel symbols per user data bit

- $\mathbf{E_b}$: energy per user data bit
- $\mathbf{E_s}$: energy per channel symbol
- $\mathbf{N_0}$: noise spectral density, watts/Hz (joules)
  - = kT; k=1.38 □ 10^{-23}; T=system temp, K
- $\mathbf{E_b/N_0}$: SNR per bit
  - dimensionless; always ≥ -1.6 dB (Shannon)
- $\mathbf{E_s/N_0}$: SNR per symbol
  - $E_s/N_0 = E_b/N_0 + 10\log_{10}(\text{code rate})$
  - can be very low - challenging demods

Channel Impairments

- AWGN: Additive White Gaussian Noise
  - Classic spacecraft channel
  - Thermal noise only, no fading
  - Very worthwhile power gains (7-10 dB)
- Fading, pulsed interference (radar)
  - Diversity, diversity, diversity!
    - time, frequency, space/polarization
  - Uncoded: *weakest* E_b/N_0; coded: *average* E_b/N_0
  - Gains potentially unlimited (tens of dB!)

Design Tradeoffs

- Block size? Data rate? Bandwidth bps/Hz?
- Fading? (none, slow or fast)
  - most critical parameter
  - influences mod/demod choice
  - interleaver depth: ≥ 10x fade duration
- Tolerable latency?
  - limits interleaver depth

Modulation Choices

- Power limited channels (most satellites)
  - BPSK
    - simple, narrow main lobe, high sidelobes
    - filtering introduces envelope variations
  - MSK
    - more complex, wider main lobe, low sidelobes
    - constant envelope
- Bandwidth limited channels (e.g., DirecTV)
  - QPSK, etc

Demodulation Choices

- AWGN channel
  - coherent, long carrier integration windows
  - low code rates OK
- Fading channel
  - coherent + residual carrier (pilot)
  - noncoherent (e.g., AO-40)
    - threshold effect sets optimum code rate ~□/□ - □/□
    - need only approximate carrier freq, no phase needed
      - loses 3-4 dB over coherent demod on AWGN

Interleaving

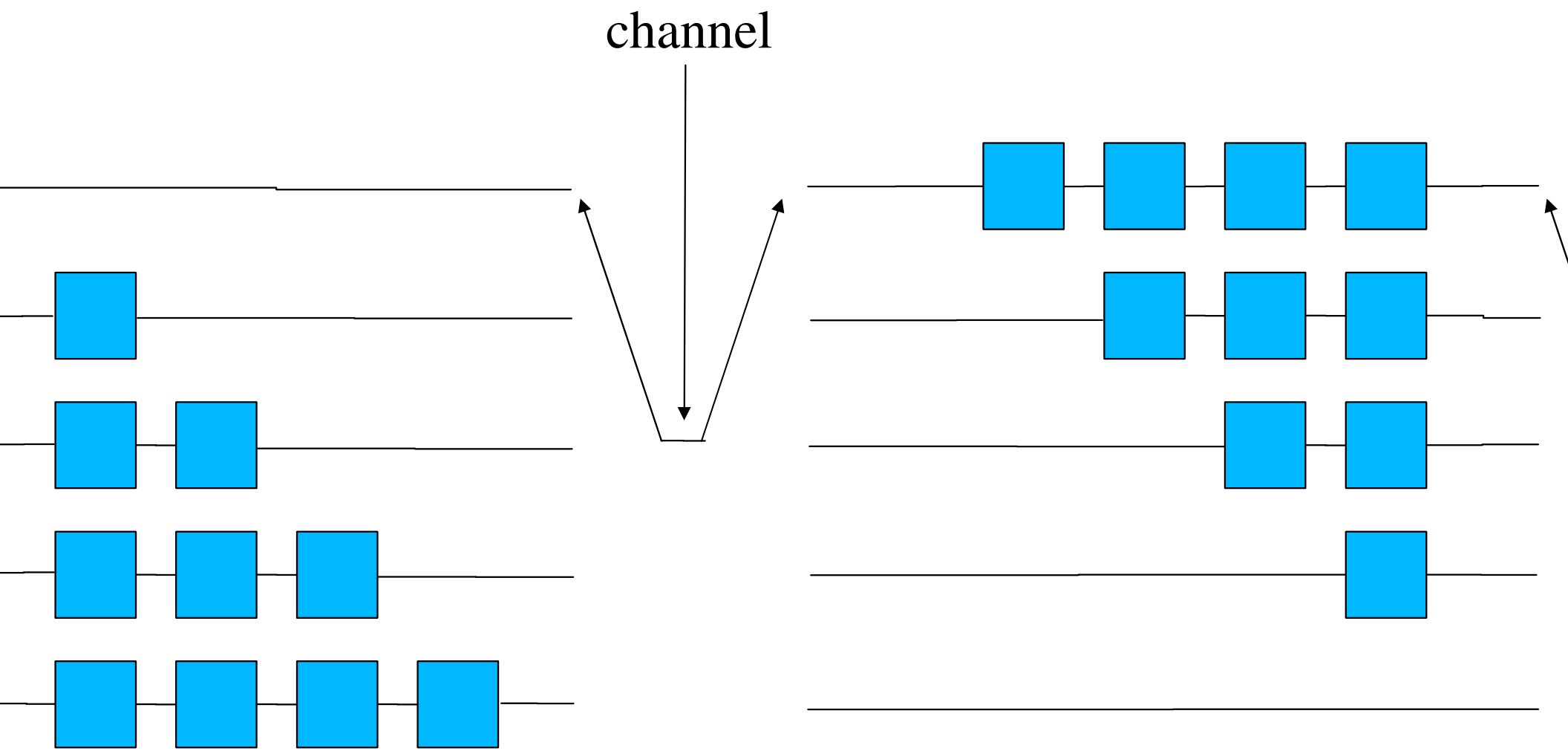
- Reorder symbols in time/freq/space
- Break up fade error bursts
  - convolutional codes especially sensitive
- Pointless without coding
- Two main interleaver types:
  - block (e.g., AO-40)
  - convolutional
    - reduces latency, especially with variable block sizes

Block Interleaving

	read cols v				
write rows -->	0	1	2	3	4
	5	6	7	8	9
	10	11	12	13	14

Sequence need not be linear;
Could be pseudo-random, bit-reversed, etc

Convolutional Interleaving



Convolutional Interleaver Sequence

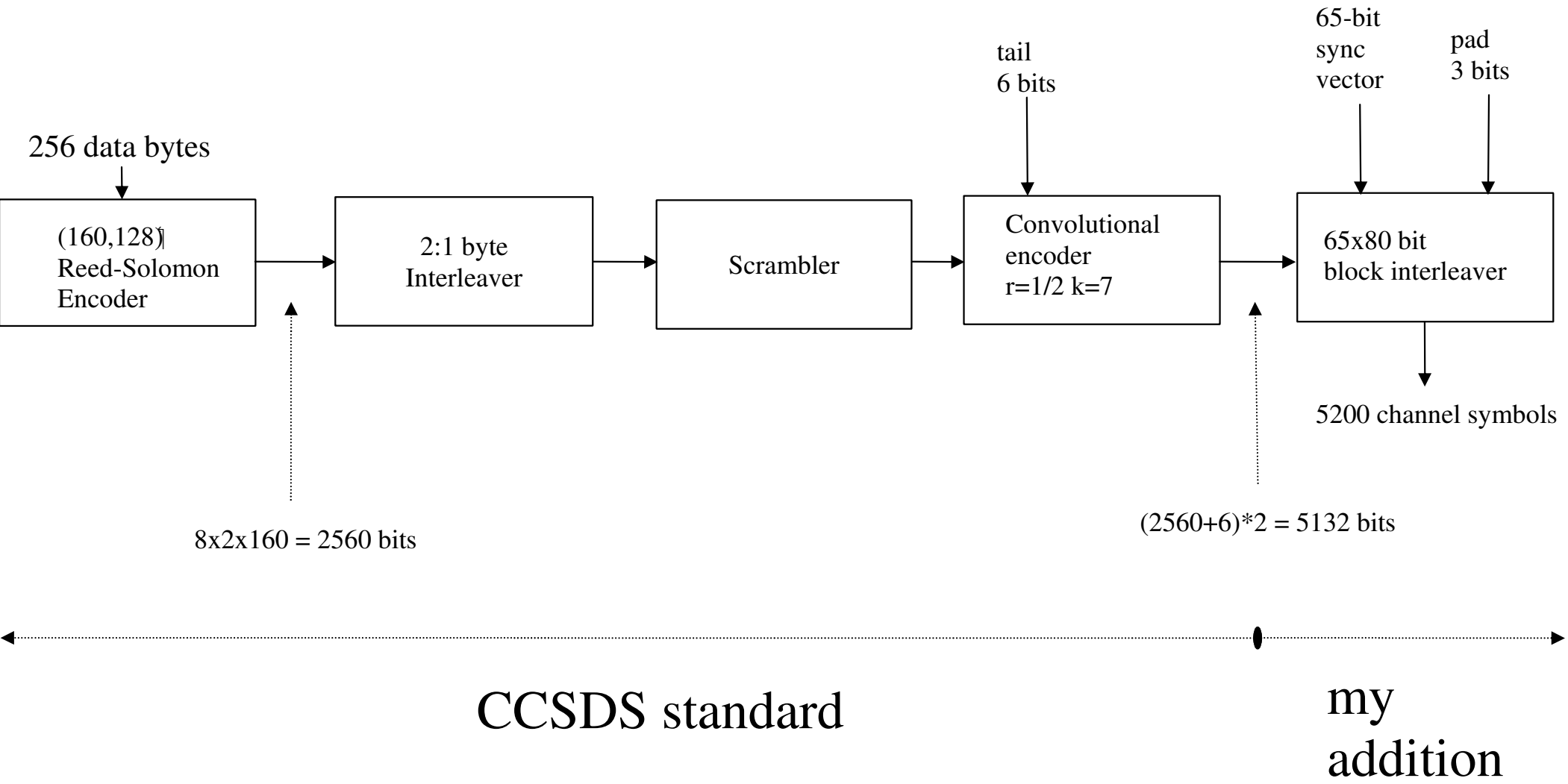
16,12,08,04,00,
21,17,13,09,05,
26,22,18,14,10,
31,27,23,19,15,
36,32,28,24,20,
41,37,33,29,25,
46,42,38,34,30,
51,47,43,39,35,
56,52,48,44,40,
61,57,53,49,45,
.....

1
6
,

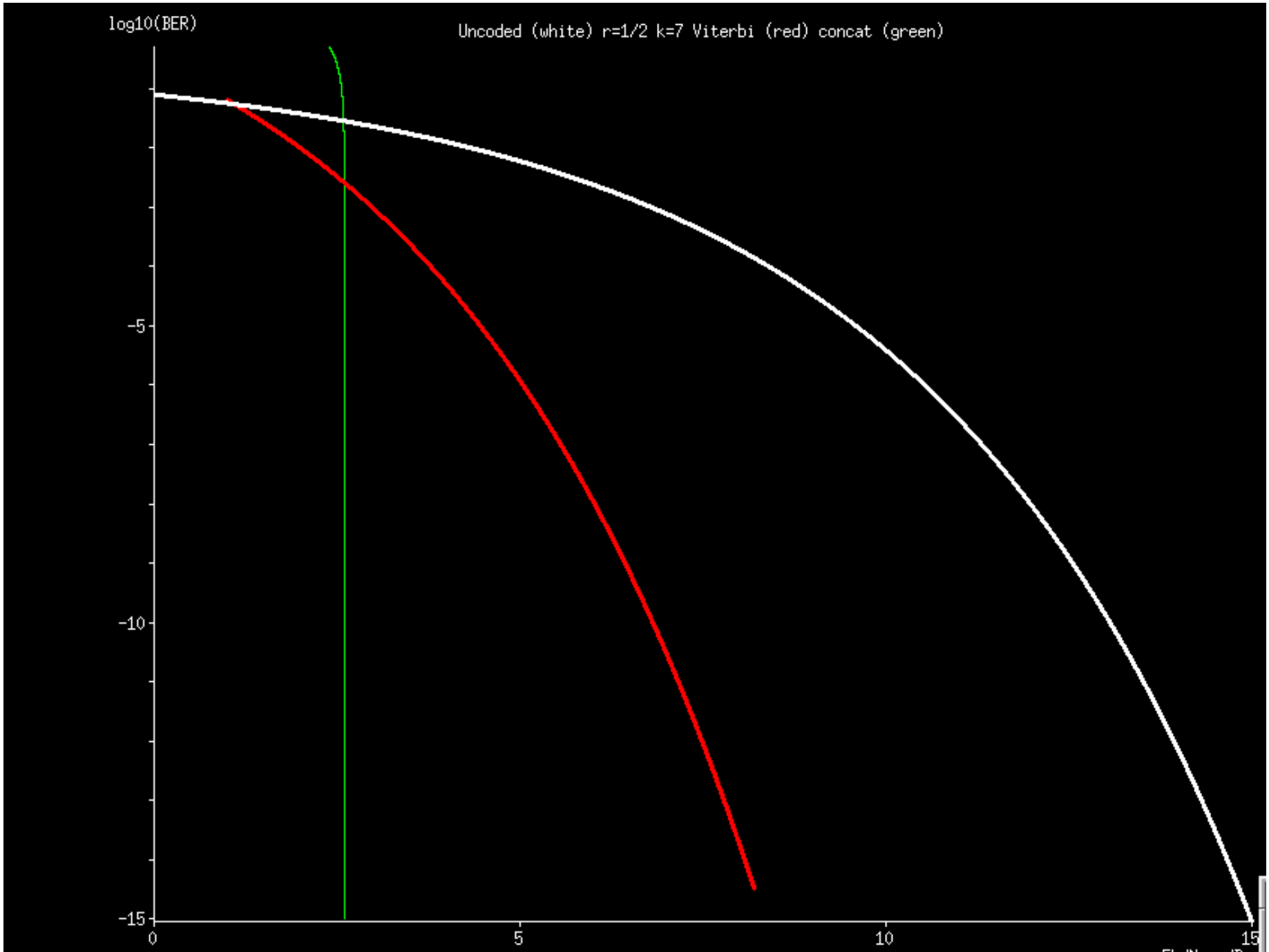
Review of AO-40 FEC format

- #1 design consideration: spin fading
- Worth sacrificing AWGN (weak non-fading) performance
- Compatibility with AO-40 IHU hardware
- Block size 256 bytes (vs 512) - binary part
- 2002 AMSAT proceedings
- http://www.ka9q.net/code/fec

Encoder Block Diagram



AO-40 FEC on AWGN



Other KA9Q Software Demods

- Advanced Composition Explorer (ACE)
  - Sun-earth L1 halo orbit
  - Real Time Solar Wind particles & waves data
    - CCSDS standard RS + k=7 r=½ convolutional
- Solar-Terrestrial Relations Observatory
  - Two spacecraft in earth's solar orbit
  - Continuous low rate telemetry & data
    - Cassini k=15 r=⅙ convolutional + CRC
    - turbo coding (when I do it)

State Estimation

- The demodulation problem *is the **state estimation** problem*
  - *Carrier frequency*
  - *Carrier phase*
  - *Symbol timing*
  - *Frame timing*
  - *Interleaver phase*
- *With these, demodulation/decoding is easy*

Traditional Hardware Demods

- Try one estimated set of parameters at a time
- Correct parameters with analog computation on undecoded signal
  - eg, Costas loop, squaring loop generate phase error
- Takes no advantage of upper layers
  - Known frame size, frame sync, FEC, decode success/fail, etc
- Can emulate in software, but *why*?

My Software approach

Read block of samples

loop:
Attempt decode at current state
Success?
    save current state as next starting state
    break;
Move state in outward spiral
end loop;

Go to next block of samples

Properties of software demod

- Brute force search of entire parameter space for each block
  - If signal is present and decodeable, it *will* be found right away - no “lockup time”
  - can't do better
- No loop instabilities
- No squaring losses
  - significant problem at low code rates
- Max CPU on noise, min tracking

Coherent BPSK Demodulation

- Optimum performance on AWGN
- Bad choice for fading channel
  - at least without pilot/carrier reference
  - carrier state (freq/phase) changes rapidly
  - may spread outside detection bandwidth
- Traditional choice for Phase 3, Pacsat

Noncoherent BPSK Demodulation

- Each symbol is phase reference for next
- Requires differential encoding at transmitter
  - Phase 3 does this in hardware
- Simple, quick acquisition
- Excellent fade performance
- Theshold effect, much like FM
  - 3 dB loss at threshold (6 dB vs 3 dB)
  - So why are most Phase 3 demods coherent??

Thoughts on Future Links

- Not constrained by existing hardware
- FEC is a no-brainer
  - mandatory on ➔➔***ALL***⬅⬅***future AMSAT links!***
  - ***FSK and especially AFSK/FM must die!!!!***
- ***Different problems need different designs***
  - ***uplinks and downlinks may differ***
  - ***encoding easier than decoding***
  - ***switchable params for variable links (Suitsat?)***

Questions?

Brickbats?

Snarky remarks?

Bit reversed block interleaving

0,8,4,12,2,10,6,14,1,9,5,13,3,7,15....

8,4,8,10,8,4,7,8,4,

0-0, 1-8, 2-4, 3-12, 4-2, 5-10,
6-6, 7-14, 8-1, 9-9, 10-5,11-13,
12-3,13-11,14-7,15-15

0,8,4,12,2,10,6,14,1,9,5,13,3,11,7,15

8,4,8,10,8,4,8,13,8,4,8,10,8,4,8